

QCD Supersymmetry and Low Scale Gravity

Alessandro Cafarella* Claudio Corianò* and T. N. Tomaras†

**Dipartimento di Fisica dell' Università di Lecce and INFN-Lecce, Via Arnesano, 73100 Lecce, Italy. E-mail: alessandro.cafarella@le.infn.it, claudio.coriano@le.infn.it*

†Department of Physics and Institute for Plasma Physics, University of Crete and FORTH, Heraklion, Crete, Greece E-mail: tomaras@physics.uoc.gr

Theories with large extra dimensions [1] invoke a brane picture of the universe, with matter confined on a brane embedded in a higher D -dimensional space ($D = 4 + N$), and only gravity free to propagate in the extra dimensions. A certain number, say n , of the N extra dimensions may be large, with size of the order of a millimeter. These scenarios are characterized by a low fundamental scale for gravity, M_* , related to the Planck scale M_{Pl} by $M_{Pl}^2 = M_*^{n+2} V_{(n)}$, with $V_{(n)}$ the volume of the extra dimensions. For $n = 2$, M_* can be of the order of a TeV if the typical size of the large extra dimensions is a millimeter. At the LHC, for QCD factorization scales above M_* , gravity becomes strong and hadronic collisions should be characterized by a rich new phenomenology. In particular, mini black holes of mass $M_{BH} \approx M_*$ are expected to be produced copiously [2] (see [3] for a discussion of some quantum aspects).

Mini black holes are hot, characterized by a temperature which is inversely proportional to their mass M_{BH} . Their formation takes place in (parton-parton) collisions for impact parameters of the order of the size of the horizon (r_H)

$$r_H = \frac{1}{\sqrt{\pi} M_*} \left(\frac{M_{BH}}{M_*} \right)^{\frac{1}{n+1}} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right)^{\frac{1}{n+1}}. \quad (1)$$

corresponding to the collision energy $E \sim M_{BH}$ in the center of mass frame. For $n > 0$ the relation between r_H and M_{BH} becomes nonlinear and the presence of M_* in the denominator of Eq. (1) in place of M_{Pl} increases the size of the horizon for a given M_{BH} . For $M_{BH}/M_* \sim 5$ and $M_* = 1$ TeV the size of the horizon is around 10^{-4} fm and decreases with increasing n . A good approximation to the partonic cross section for producing a mini black hole is $\sigma_{BH} \approx \pi r_H^2$, the geometrical one. It can be folded with parton distributions ($f(x, Q^2)$) to give predictions, for instance, for total cross sections

$$\sigma(pp \rightarrow BH + X) = \frac{1}{s} \sum_{a,b} \int_{M_{BH,min}^2}^s dM_{BH}^2 \times \int_{x_{1,min}}^1 \frac{dx_1}{x_1} f_a(x_1, Q^2) \sigma_{BH} f_b(x_2, Q^2), \quad (2)$$

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where x_1 and $x_2 = M_{BH}^2/(x_1 s)$ are the momentum fractions of the initial partons and $x_{1,min} = M_{BH}^2/s$. The factorization scale Q is of the order of $1/r_H$. The absorption/emission cross section depends sensitively on the greybody factors of the black hole, which are energy dependent. The choice of either constant or full energy-dependent greybody factors, which are known for static (Schwarzschild) mini black hole solutions [4], gives widely different results [5]. The known analytical expressions of the greybody factors at low frequencies are of limited help in the prediction of the event rates at the LHC, but these can be computed numerically [6]. Of particular relevance would be the numerical study of the greybody factors for Kerr solutions, since black holes, in general, will be produced with non-vanishing angular momentum.

Studies of the p_T distributions show a much larger signal compared to the fast falling QCD background [5], even for M_* as high as 5 TeV, starting at $p_T \sim 50 - 200$ GeV and up. The dependence on the number of extra dimensions n is also significant. A second sensitivity in the prediction of event rates comes from the integration over the invariant mass M_{BH} for M_{BH} close to M_{Pl} , since the semiclassical picture of the formation and decay of the black hole is not valid any longer. In all the studies presented so far larger multiplicities of the final states and broader p_T distributions appear to be a striking signature of mini black hole formation in hadron collisions. In the most optimistic scenario in which both low energy gravity and supersymmetry will be discovered at the LHC, then the multiplicities of the final state in the decay of the black hole should grow even faster from what inferred from these studies. However, it is important to keep in mind that a part of the energy available in the collision is lost into gravitational emission, and only a fraction of it remains available for the hadronization, which would imply reduced multiplicities.

The time scales for the black hole decay into partons and the QCD hadronization scale are largely separated and the decay of the black hole is, essentially, instantaneous. Hadronization takes place soon after the partons, which are emitted in an approximate s-wave, cross the horizon. The emissions of single partons are assumed to be uncorrelated, and can be described by a multinomial distribution, while the hadronization is studied either using Monte Carlo [7] or renormalization group equations [8].

The computation of the cumulative probabilities to produce any number (K) of hadrons of type h by the decay of the black hole are obtained from the multinomial distribution multiplied by the fragmentation probabilities of each elementary state to h and summing over all possible emissions [8]

$$\text{Pr}_{\text{cum } h}(K, Q) \equiv \sum_{n_f, n_i} \frac{K!}{\prod_f n_f! \prod_i n_i!} \prod_f \left(p_f < D_f^h(Q_F) > \right)^{n_f} \prod_i \left(p_i < D_i^h(Q_F) > \right)^{n_i}, \quad (3)$$

where i is summed over gluons, photons and a set or remainder states, f runs over the quark flavours, while $K = n_f + n_i$. In (3) the $< D_{i,f}^h(Q_F) >$ are the first moments of the fragmentation functions of a parton/photon k to a hadron h at a scale Q_F . The sum is over all the main hadronic states. The fragmentation scale Q_F is related to the number of fundamental decaying states N_m to which the black hole couples in a democratic way and to its mass M_{BH} by $Q_f = M_{BH}/N_m$, where our knowledge of the multiplicity N_m is clearly approximate. Obtaining a good estimate of N_m is important for studies of the multi-jet structure of the events at the LHC, but is less relevant for cosmic ray studies.

In this latter case the evolution of the air shower after the decay of the black hole washes out the information on small variations in the original multiplicities in the decay. At this time, the only known formulas available for N_m come from a semiclassical analysis. We recall that in cosmic ray physics mini black hole events can be triggered by neutrinos scattering off nucleons in the atmosphere. An analysis of the lateral distributions of showers and of the corresponding multiplicities shows that intermediate mini black hole resonances are respectively much wider and larger compared to ordinary air showers [8], in agreement with the fireball picture of the decay which has emerged from LHC studies.

Proposals for the best approximation to N_m are several. In [2] was suggested to use

$$N_m = \frac{2\pi}{n+1} \left(\frac{M_{BH}}{M_*} \right)^{\frac{n+2}{n+1}} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right)^{\frac{1}{n+1}} \frac{1}{\sqrt{\pi}}, \quad (4)$$

but there are variants of it. Other expressions include a correction factor ρ coming from a more detailed analysis of the Hawking formula for the semiclassical decay which takes into account the corresponding greybody (Γ_s) factors more accurately [9]. Then $N_m = \rho S_0$ with S_0 being the entropy of the black hole and

$$\rho = \frac{\sum_s c_s f_s \Gamma_s \Gamma(3) \zeta(3)}{\sum_s c_s f'_s \Gamma_s \Gamma(4) \zeta(4)}, \quad (5)$$

which is expressed in terms of the greybody factors and certain numerical coefficients (c_s, f_s, f'_s) dependent on the spin s of the fields propagating over the black hole background. As we have already mentioned, the issue of gravitational energy emission during the formation of the black hole and during its decay remains open. Work in this direction can follow closely some of the recent results on the study of quasi-normal modes for ordinary black holes in 4 dimensions aimed at the detection of gravitational waves [10].

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